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TITLE: FAST-EXTRACTION MODULATORS FOR LOS ALAMOS SCIENTIFIC LABORATORY PROTON STORAGE RING

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FAST-EXTRACTION MODULATORS FOR LOS ALAMOS SCIENTIFIC LABORATORY PROTON STORAGE RING

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Introduction

The Proton Storage Ring (PSR) now being designed at the Los Alamos Scientific Laboratory (LASL) will accumulate 800 MeV of protons from the Los Alamos Meson Physics Facility linear accelerator and deliver them in intense bursts to neutron production targets at the Weapons Neutron Research Facility. Two modes of operation are planned. In the short-bunch mode, the protons are accumulated for 110 μs into six circulating bunches, each of nanosecond width every 8.3 ms, and are extracted at a rate of 720 bunches/s. In the long-bunch mode, a single 270-ns bunch is accumulated in 750 μs every 67 ms. Each bunch is extracted within a few microseconds after accumulation is completed. The circulation period of protons in the PSR is 360 ns.

Design and Reliability Considerations

A bunch trajectory deflection of 6 mrad is required for extraction from the PSR. This requires a magnetic field path of 300 G-m (Gauss-meter). Because of the requirement for fast risetime and good pulse fidelity, the "magnet" is a parallel-plate transmission line 4 m long, schematically illustrated in Fig. 1. The force on a proton moving between the plates is $F = q(E + V \times B) = qE(1 + \beta)$, where $\beta = v/c = 0.84$ is the proton velocity expressed as a fraction of the velocity of light, and $|cB| = |E|$ for TEM wave propagation in vacuum. The deflection pulse is propagated in the direction opposite that of the protons to get additive effects of electric and magnetic forces.

The two sides of the transmission lines are driven with pulses of opposite polarity, resulting in a virtual ground at the midplane. The impedance seen by the pulse generator is 50 Ω for each plate relative to ground. For a 10 cm aperture (separation between stripline elements), a voltage of ±50 kV is required. The pulse parameters for the short- and long-bunch-mode modulators are listed in Table I.

A number of design requirements follow from the application of the modulators in a working accelerator facility. Because of the limited downtime acceptable to the user and the limited operating budgets, all of the modulator components must have a long lifetime. High reliability is essential since the consequence of improper deflection is beam spillage, which makes the PSR radioactive. Thus the failure rate in the long-bunch mode should not exceed 10^{-4}.

TABLE I
PSR FAST EXTRACTION MODULATOR
PULSE PARAMETERS

PARAMETER	SHORT BUNCH MODE	LONG BUNCH MODE
PURPOSE	Remove Single 1ns Proton Bunches	Remove Single 270 ns Proton Bunch
PULSE VOLTAGE	(+) & (−) 50kV	(+) & (−) 50kV
PULSE CURRENT	(+) & (−) 1kA	(+) & (−) 1kA
PULSE RISETIME	< 30ns	30ns
PULSE FALLTIME	< 30ns	Not critical
PULSE BASE WIDTH	< 80ns	360ns
PERCENT AFTER PULSE RINGOUT	< 2%	Not critical
PULSE REPETITION RATE	720Hz	12 120Hz
PEAK POWER	100MW	100MW
AVERAGE POWER	4.3kW	0.43 4.3kW

Pulse-Generator Systems

The development of the short-bunch mode, fast-extraction modulator prototype is detailed in this report. Similar systems will be used for the long-bunch mode, fast-extraction modulator. The short-bunch-mode modulator presents the largest technological challenge; the long-bunch modulator problems are similar but less demanding.

A symmetrical generator system is desired to reduce the deflection voltage levels required with respect to ground. In addition, it is desirable to use some type of voltage multiplication system to reduce the required switch operating voltage and thus increase reliability. Several pulse-forming network (PFN) type pulse-generator systems were evaluated because of the square pulse shape desired. The requirement for minimum prepulse favors a switched PFN that prevents charging transients in the load as shown in Fig. 2a. However, the switch of Fig. 2a must operate at twice the desired output voltage, and some form of voltage inversion (transformer) or double, oppositely charged, system must be used to obtain the required push-pull output. The basic Blumlein system of Fig. 2b can be used to reduce the switch operating voltage to that of the desired output-pulse voltage, but the line charging current must flow through the load, causing a prepulse. A dual, oppositely charged, Blumlein-line scheme can be configured to provide push-pull outputs as shown in Fig. 2c, but again the switch must operate at twice the single output voltage and must be dc isolated with respect to ground for the charging potentials.

A new Ferrite-Isolated Blumlein-(FIB) line circuit was developed at LASL to alleviate the above problems and is shown in Fig. 3. This circuit uses one element to switch two Blumlein lines in parallel (instead of in series as in Fig. 2c) and ferrite inductive isolation to provide bipolar output pulses. Computer network analysis indicates that the sum of the output pulses is ±0.01% of the absolute value of each. The FIB line circuit can also reduce the charging currents that flow

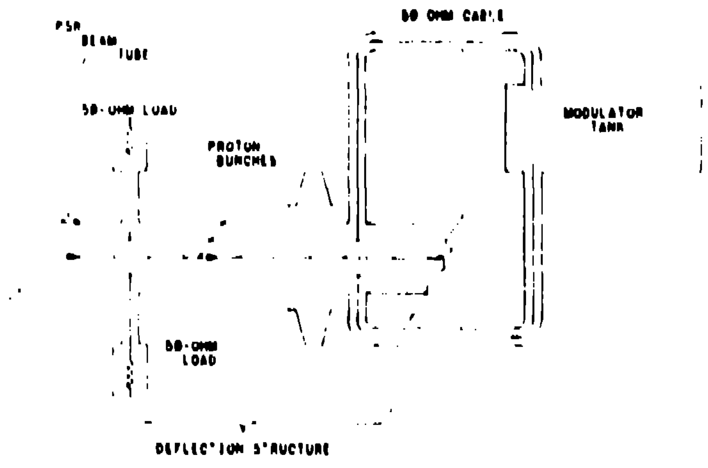
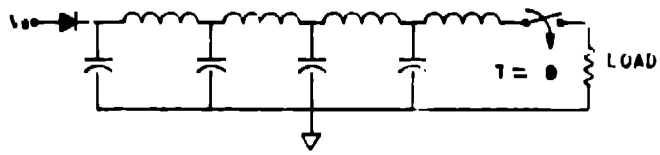
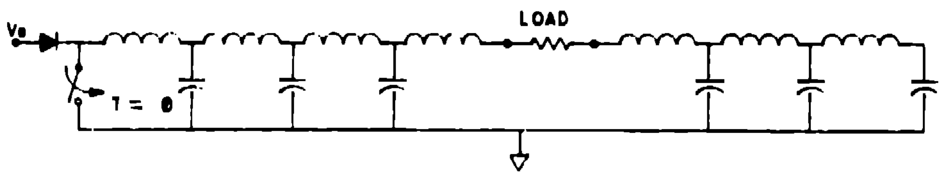


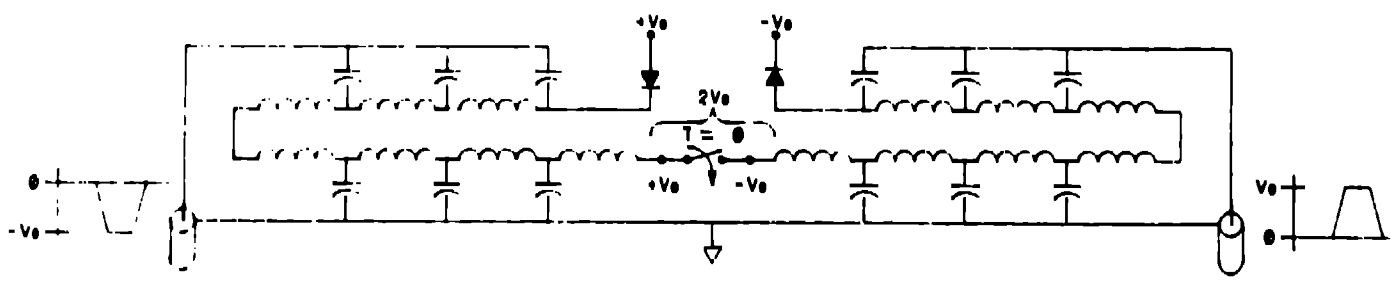
Fig. 1. PSR extraction modulator schematic.



(A) SWITCHED PFN CIRCUITS



(B) BASIC BLUMLEIN LINE CIRCUIT



(C) PLUS-MINUS DUAL BLUMLEIN LINE CIRCUIT

Fig. 2. Pulse generator circuits.
(A) Switched PFN circuit.
(B) Basic Blumlein-line current.
(C) Plus-minus charged dual Blumlein-line circuit.

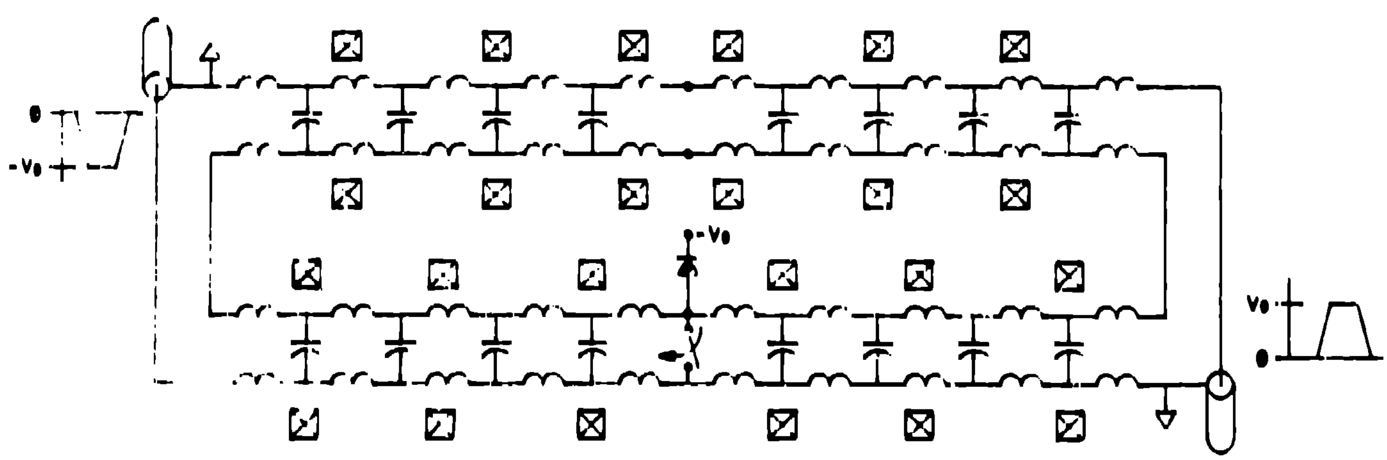


Fig. 3. Ferrite-Isolated Blumlein (FIB) circuit.

through the loads. If the circuit is charged at two points from the same source, the prepulses can be reduced to <1% of the output voltage.

The pulse-generator system of Fig. 3 was fabricated using 45 ns (15 ft), 23-Ω coaxial cable (17/14) lines and 50-Ω output cables. Sixty Ferrocube Type C38, 2-in. o.d. ferrite toroids per line provide sufficient inductive isolation for the short-bunch mode when the cable is threaded through them, as shown in Fig. 4. The assembly is switched with an EG&G HY-3024 gradient-grid thyratron for increased voltage hold-off reliability. The tube is mounted, as shown in Fig. 5, in a low-inductance shroud on an EG&G TM-42HV isolation system. The switch tube rises to one-half the output voltage during the pulse. Initially, the tube was triggered with a 2.5-kV positive pulse (unloaded) from an SCR-switched PFN added to the negative bias at grid G2 and a positive bias on G1, as shown in Fig. 6a. The resulting pulse shape, shown in Fig. 6b, indicates an unacceptably long turn-on time for the tube. Several other trigger configurations were investigated and are shown with their resultant output pulses in Figs. 7 and 8. The jitter for the trigger arrangements of Figs. 6-8 was excessive, ranging from ±10 to ±200 ns. A trigger booster consisting of an 8.5-Ω, 1-μs PFN switched by an EG&G HY-6 thyratron in the cathode follower circuit of Fig. 9a was inserted between the original trigger unit and the HY-3024. Three overlays of the resulting output pulse shape are shown in Fig. 9b, indicating low total system jitter (1-2 ns) and very good circuit-limited pulse shape. The voltage on the trigger booster was reduced from 4 kV to 1 kV with little deterioration in pulse rise- and falltime (< 10% increase). The delay time from booster anode voltage fall to HY-3024 anode fall is about 55 ns. The trigger booster pulse length was reduced from 1 μs to 250 ns without any observable change in delay, jitter, or output pulse shape. Note that the after-pulse ringout is greater than that desired, but can be reduced by matching the pulse generator to the load more closely.

Charging System

The charging system is required to charge the Blumlein lines (~ 5 nF) to 50 kV. The desire for high reliability is manifest in the choice of a charging system that uses a combination of resonant and transformer pulse charging. The charging circuit is shown

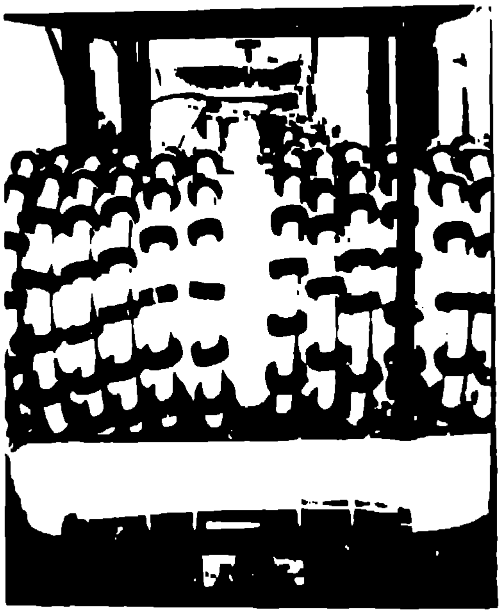


Fig. 4. FIB line.

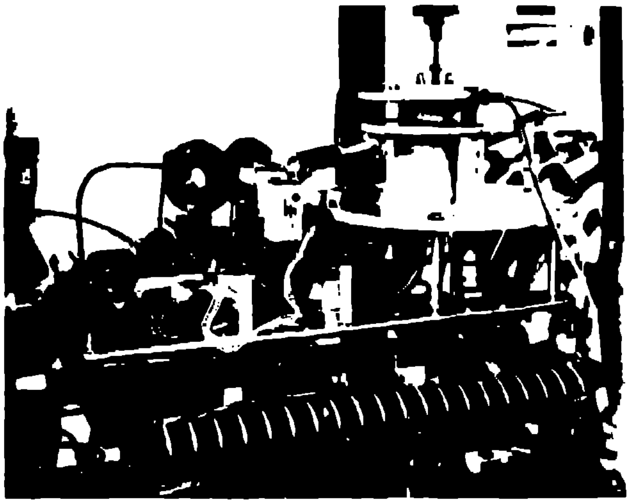


Fig. 5. Thyratron shroud and deck.

in Fig. 10. Ideally, a 10:1 voltage step-up transformer would be used to charge the Blumlein lines to 50 kV from an intermediate capacitor resonantly charged to 5 kV. However, the stray capacitances are a sizable fraction of the FIB line. Thus the intermediate energy storage capacitor must be resonantly charged to 6.2 kV in order to charge the FIB line to 50 kV. The intermediate energy storage capacitor is resonantly charged in 250 μs. Then the transformer system charges the Blumlein lines to 50 kV in ~4 μs. The main Blumlein-line switch is triggered within 100 μs after charging so that the high-voltage system is energized for only a short time, reducing prefire probability. The transformer backswing also assists in turning off the charge thyratron (initially an EG&G HY-3025) so that both switches are not closed simultaneously to reduce fault problems. The charge thyratron is a 25-kV unit, but it is operated at only 6.2 kV to reduce prefires and increase reliability. The voltage on the intermediate energy storage capacitor is regulated with a reactive de"Q" circuit[4] also illustrated in Fig. 10. The voltage on the intermediate capacitor is monitored during the charging cycle and the de"Q" switch is closed when the voltage reaches the desired value. Closing the switch returns any residual energy stored in the charging choke to the low-impedance power-supply filter capacitor and thus prevents the intermediate energy storage capacitor from charging further. The charge thyratron and blocking diodes require the largest average and rms currents. The switch-tube and diode requirements are listed in Table II. The charge thyratron will probably have to be a 5-in. EG&G tube (173 A rms) to provide reliable long-life operation at the 43 A rms current required. A complete computer

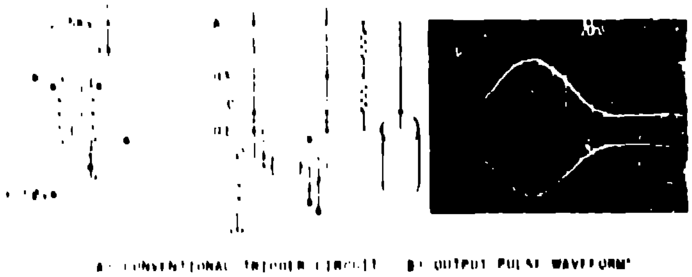


Fig. 6. Initial trigger circuit and pulse output.

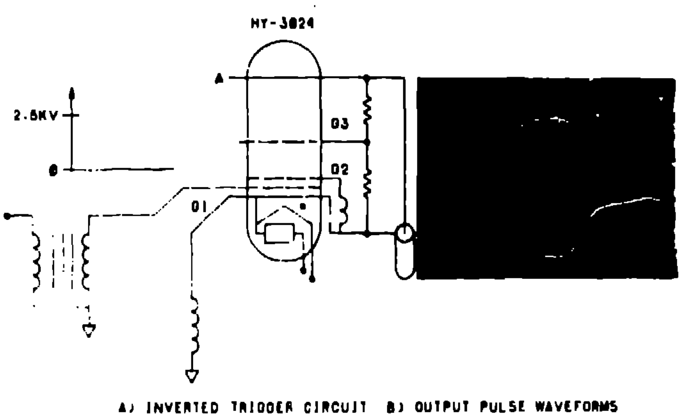


Fig. 7. Inverted trigger circuit and pulse output.

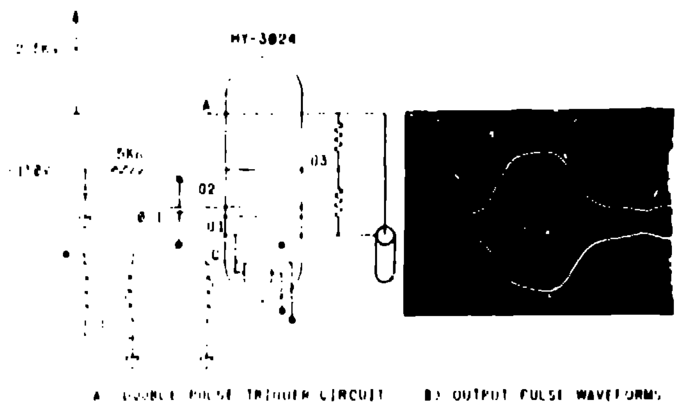


Fig. 8. Double pulse trigger circuit and pulse output.

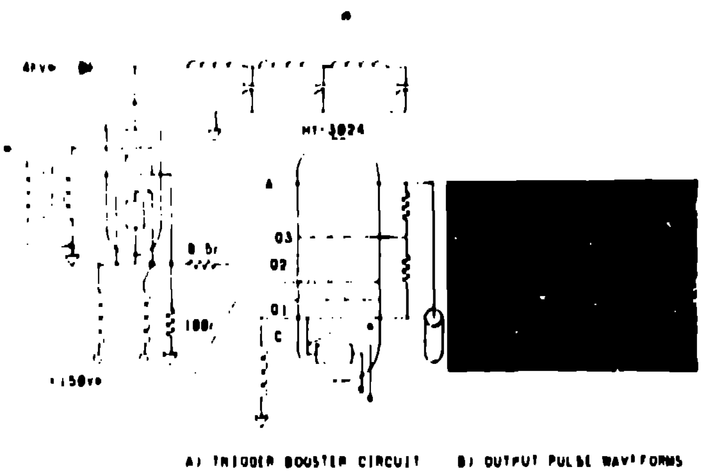


Fig. 9. Trigger booster circuit and pulse output.

TABLE II

SHORT-BUNCH MODE
EXTRACTION MODULATOR SWITCH AND DIODE PARAMETERS

Parameters	Charging Switch	Output Switch	Charging Diode
Operating voltage	6.2 kV	50 kV	50 kV
Peak current	1.3 kA	4.3 kA	120 A
Repetition rate	720 Hz	720 Hz	720 Hz
Pulse width	3.5 µs	50 ns	250 µs
Average current	2.0 A	1.5 A	2.0 A
RMS current	43 A	18 A	6.0 A
Lifetime	$\geq 10^4$ H	$\geq 10^4$ H	$\geq 10^4$ H

model of the charge system was used to check the thyratron performance and the charging efficiency of the transformer circuit. The system charging, excluding the power supply, is about 80% efficient for this particular circuit; most of the energy is lost to the transformer stray capacitance, which is close to 10% of the Blumlein-line capacitance. The remainder is lost in the charge thyratron, the diode snubber, the diode forward resistance, and the transformer magnetizing reactance.

Charging Diode Tests

The charging diodes for the fast (4 µs) transformer charge system present several unusual requirements. First, the rms and average currents are large, as listed in Table II. Second, the charging diodes must turn on in less than one-tenth of the current pulse to prevent large anode dissipation, and must recover in less than one-tenth of the current pulse time to prevent energy from returning to the transformer primary energy store. Several manufacturers' diodes were tested for I-V turn-on characteristics, and also life tested singly at the current levels and repetition rates present in the actual circuit. The voltage and current waveforms for several diodes from different manufacturers are shown in Fig. 11.

System Considerations

The entire modulator system is mounted on a hydraulic scissor lift table inside a tank of transformer oil, as shown in Fig. 12. The output cables are routed to the deflection structure within the proton storage ring and then on to 50-Ω loads for dissipation. The lift table permits easy access to the components for modification and maintenance. Two separate kicker systems (short-bunch and long-bunch modes) will be used separately with the same deflection structure. The modulator system will be equipped with computer-programmable time-delay units and power supplies to permit

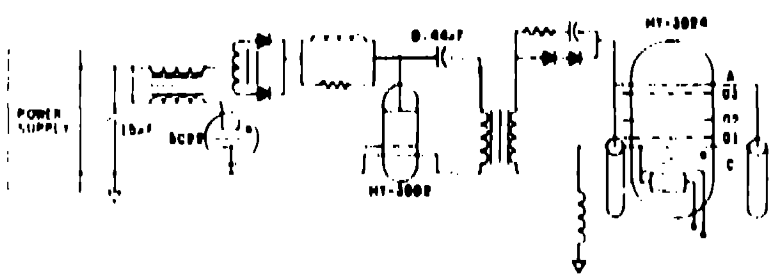


Fig. 10. Two-stage resonant and transformer charge circuit.

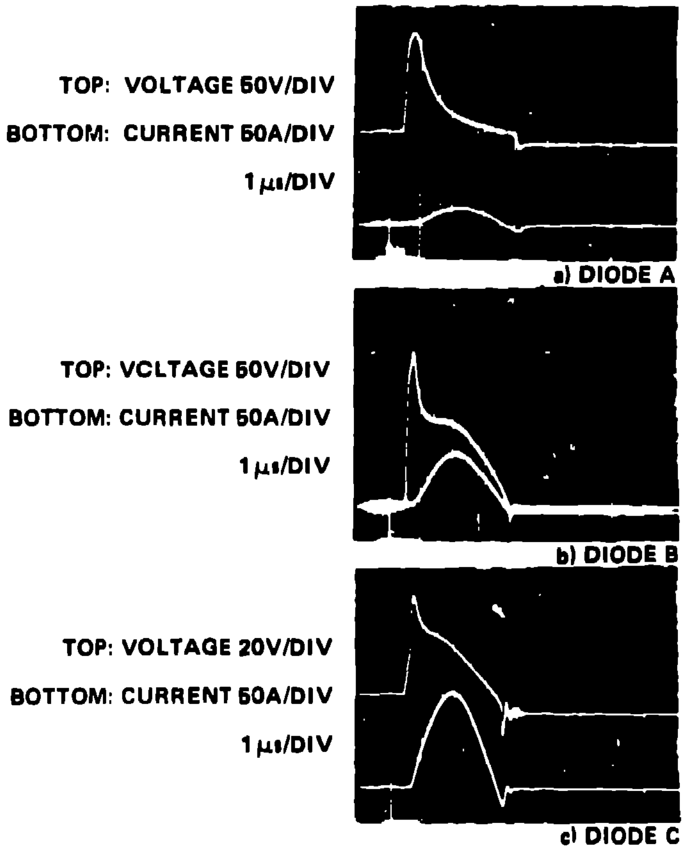


Fig. 11. Diode voltage and current waveforms.

computer control. The time-delay units will be interfaced to the modulator system by LASL fiber optic trigger links.

Life test of the prototype system and components at the desired operating conditions will provide reliability data for the final modulator systems.

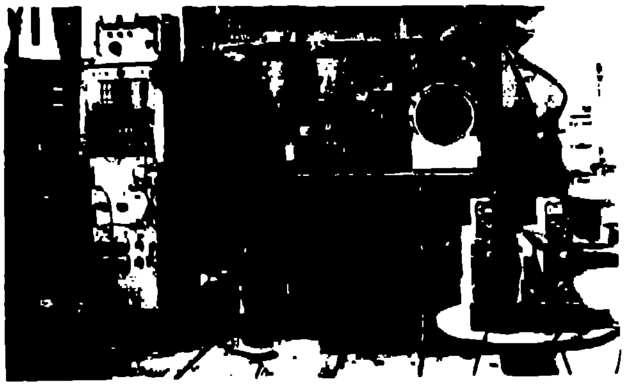


Fig. 12. Picture of short-bunch-mode modulator prototype.

Conclusions

The development of a short-bunch mode fast-extraction modulator for the LASL proton storage ring has made necessary the design and development of a resonant transformer charging circuit and the design of a new FIB line circuit to provide bipolar pulse outputs with low prepulse, postpulse, and an optimum high-voltage switch environments. The systems are now being developed to operate reliably at the high-average powers required. The short-bunch mode fast-extraction modulator prototype is presently operating. The initial construction of the long-bunch mode fast-extraction modulator prototype is under way, with results expected within the year.

References

1. G. T. Coate, L. R. Swain, Jr., High-Power Semiconductor-Magnetic Pulse Generators, MIT Press, Cambridge, Massachusetts, 1966, pp. 57-67.